THE POWERSTICK

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Abstract

In the pursuit of faster, better, cheaper, the Jet Propulsion laboratory (JPL) is scaling down all of its missions. "Battle Star Galacticas" are replaced with micro spacecraft and moon mining trucks succumb to micro rovers. Micro devices take advantage of technological progress in miniaturization, microchips, micro gears and lightweight structures. Just about every spacecraft subsystem has gone through a shrinking process.

The only heavy spacecraft component that has resisted change is the power source. JPL, earlier this year, studied the feasibility of Mars Network Mini-Met stations and micro rovers. These space vehicles will have very limited missions unless a device like the Powerstick is developed. These missions shy away from Radioisotope Thermoelectric Generators (RTGs) because of the unavailability of small units and the high costs to develop them.

The Powerstick satisfies all the demands for a power source for these small missions at a potentially very small price. Powerstick is a miniature power source that consists of a Radioisotope Heater Unit (RHU), a thermoelectric thermopile and a bank of small batteries. The RHU is a spot heater produced by DoE and commonly used on spacecraft. The RHU is used in the Powerstick as a source providing heat to a thermoelectric element. It appears that the powerstick, using a single RHU and a bismuth-telluride thermoelectric converter, is capable of producing 42 milliwatts at 15 voltsat the beginning of life. This would reduce to 37 milliwatts at **14** volts after 10 years of operation. This electricity would trickle charge the lithium batteries providing peak power to a micro rover, a mini meteorological station or a micro spacecraft.

The attractive feature of the Powerstick is its potential for low development cost. The final design of the powerstick must assure that there is no need for requalification of the RHU. Without such a requalification, the development cost of the Powerstick will be quite low.

Importance of the Powerstick

Many small autonomous robotic packages cannot be outfitted with solar panels because of large array size, difficulties in array orientation, or damage due to planetary or comet dust environment. On Mars, just like on Earth, solar power is effective only close to the equator. For a global coverage with such small packages as miniature seismometers, mineral scouts and in-situ meteorological sensors, the only existing power sources are batteries that can last only for several hours, The availability of a Powerstick would alleviate all the above problems with solar arrays and batteries for all micro instruments developed for a planetary program.

The development of a Powerstick will have a great impact on the whole micro-world. The Powerstick may be used in any autonomous science package that either uses continuous power at a level of a fraction of a watt or can operate intermittently by using energy from the batteries. There are several such micro devices currently being investigated at JPL. For example, a micro seismometer is being developed that requires less than 1 watt to operate. The next generation of seismometers is expected to consume no more than 0.1 W. Seismometers require power sources that can last for years due to the sporadic nature of seismic events. An alpha-proton-x-ray spectrometer that is being developed for small rovers to investigate rock composition would require about one third of a watt, which again is within the range of a Powerstick. The next generation of cameras using principles of active pixel sensors could operate consuming only a fraction of a watt.

There are also a number of micro spacecraft instruments and subsystems that could operate using distributed instead of centralized power. instruments such as magnetometers that must be located on extended booms are perfect candidates for distributcd power. Powcrsticks could also supply spot heating to the dcviccs they power. Such an approach could bc considered for a micro spacecraft.

The Mars Environment Survey (MESUR) Network mission studied earlier this year sclcctcd the Powcrstick as the baseline power source for its Mini-Meteorological stations. Powcrsticks would produce enough continuous power to operate a scqucnccr while trick lc charging the batteries. The battery power would bc used every fcw weeks to operate the instruments and transmit the data. Without a dcvicc like the Powcrstick, it will bc difficult to opcratc any dcviccs in thc polar regions of Mars.

A Powcrstick could also bc carried on a micro rovcr rclcascd by a lander. It would incrcasc the mission life from a fcw days to years. The Powcrstick could propel a micro rover a fcw hundrcd meters in a day, followed by a charging Cycle, scientific mcasurcmcnts and data transmission and another charge cycle. This scqucncc could bc rcpcatcd for years enabling vast terrain covcragc.

Current Design Efforts

'1'0 ascertain the feasibility of the Powcrstick concept, a small amount of JPL internal research funding was obtained to build a prototype. The initial objcctivc of the prototype dcvclopmcnt is to idcntify the rcquircmcnts for the Powcrstick. It is important not to bc shortsighted and to design the Powcrstick to support a variety of future missions. A survey of applications of a Powcrstick for instruments on micro spacecraft, micro rovers, deployable autonomous instruments for planetary surfaccs and autonomous scnsors will bc performed to establish the power, size, weight and radiation rcquircmcnts for space power Replications,

The main objcctivc of this work is to design and build a prototype of a Powcrstick. A successful prototype of a Powcrstick may open the door to a whole ncw class of space power sources. The operation of this dcvicc will bc demonstrated using an electric heat source. An electrically heated RHU was obtaincd from the Galileo project to serve as a simulator. Several Bi-Te thcrmopilcs arc being procured from the old military and paccmakcr programs. Finally, "AA" lithium titanium disulfidc1AH batteries will bc obtained from the manufacturer who supplies thcm for testing on an ongoing NASA program. The Dcpartmcnt of Energy is helping the design effort by providing guidance and critique of approaches via its consultant, Fairchild Space. The final objcctivc of the Powcrstick prototype effort is to establish a dcvclopmcnt plan, including schcdulc and cost, for a space qualified powcrstick. That activity will also bc conducted in cooperation with the personnel from DoE and Fairchild Space.

Technical Background

The Powcrstick was conccivcd to ovcrcomc some of the non-tcchnical shortcomings of the Radioisotope Thermoelectric Generators (RTGs). The Powcrstick will usc a Radioisotope Heater Unit (R II U), which is an off-the-shelf, DoE produccd itcm, that has already been qualified for the Galileo and Cassini missions. The Powcrstick will not require any technological breakthroughs. The RHU, as mentioned before, can bc purchased from DoE, the batteries arc already under dcvclopmcnt by the JPL battery group and all the other components arc readily available. The novelty of the design lics in utilizing all of these componcnts in a mutually complementary dcsign as explained below.

The RHU is a heat source designed to provide 1 W of thermal power in a package roughly the size of a 11-cell battery. The entire unit is a right circular cylinder 32 mm high, 26 mm in diameter and weighs 40 grams [1]. The graphite heat shield and thermal insulation package is sufficient to maintain the integrity of the fuel pellet even under worst case rc-entry conditions. A large number of these units were used to provide local heating on the Galileo spacecraft and arc baselincd for usc on the upcoming Cassini mission, The heat from the RHU would also bc used to maintain the tcmpcraturc of the batteries and the microchip convcrtcr, and the reject heat also could bc used to provide spacecraft heating, if desired. As can bc seen, the RHU, when used within a Powcrstick, would serve a dual role as a source of electrical power, as wcll as a heater,

The Powcrstick will usc $LiTiS_2$ rcchargcablc batteries. These arc state-of-the-art batteries that boast 120 Wh/kg cncrgy densities, which is about 3-4 times that of the popular nickel-cadrnium.

The “AA” 1 Ah ccll batteries arc currently under dcvclopmcnt sponsored by National Aeronautics and Space Administration Headquarters, Code C. The prototype of these cells can bc purchased from the manufacturer. The prototypes will have the same performance as the flight cclls, but will no! bc spacc qualificd. The Powcrstick will usc 14 cclls in two banks giving an average output of 2 Ah at 14 volts. This voltage can bc clown regulated to the user voltages by a microchip regulator or DC-DC convcrtcr. Such a convcrtcr can output a combination of 12, 5 or 3.5 volts with an efficiency of 85%. Bccausc of the very small chargc current, it is not cxpcctcd that a battery charge circuitry will bc nccdcd.

Design Considerations

A Powcrstick, which uscs an RHU, imposes numerous rcquircmcnts on the design of the thcrmoclcctric convcrtcr. To gcncratc the electric power from a single RHU with a voltage of 510 ?70 VDC, many thcrmoclcctric couples must bc conncctcd in series. The RHU has a very low thermal flux; about 0.2 W/cm^2 if all of the heat could bc dircctcd through onc end. This can bc conccntratcd by about 10 fold, through the usc of a heat collector, but the rcquircmcnt for many couples in series limits the amount of concentration. The combination of many couplcs in series and a low heat flux, means that the legs nccd to have a very small cross-section and bc very long. In order to ameliorate this problcm somewhat, it would bc dcsirablc to limit the tcmpcraturc diffcrcntial across the thcrmoclcctric convcrtcr. This serves two purposes: it rcduccs the required lcg lcngths and rcduccs the parasitic losses from the sides of the RH U. Howcvcr, it also rcduccs the conversion cfficicncy, thcrcforc, it is crucial to have a material with a very high figure of merit.

Four different thcrmoclcctric matcrials were evaluated to dctcrminc which would give the best performance in association with the Powcrstick. Thcsc materials were: silicon-gcrmanium, lcad-tclluridc, bismuth-tclluridc and advanccd materials currently being dcvclopcd by JPL. Of these matcrials, it appears that bismuth-tclluridc is the prcfcrrcd matcrial for this application. It has the highest figure of merit and is best when opcratcd at rclativcly low tcmpcraturcs (below 200°C). Operating the convcrtcr at low tcmpcraturcs makes it easier to clcctrically isolate the thcrmoclcctric legs and will rcducc material degradation and interaction problems.

Several companies have already fabricated modules with bismuth- -tclluridc, which have legs which arc 0.30 to 0.38 millimeters by 0.30 to 0.38 millimeters in cross-section and arc 12 to 15 millimeters long. Thcsc were dcvclopcd and fabricated for nuclcar powcrcd cardiac pacemakers [2]. The legs arc electrically separated from each other by Kapton, with epoxy used to bond all of the legs together into a module. Evaporated gold was used to electrically interconnect the N and P legs together intoa scrics array. The modulc would bc electrically insulated from the heat sourcc using Kapton. The thermal intcrfacc would come from a pressure contact (intcrfacc pressure in cxccss of 1 mcgapascal) to the heat source using bcllcvillc washers. The cold side would bc bondcd to a radiator to provide cooling.

Analysis

A finite diffcrcncc thermal model of the RHU was gcncratcd. It was used for thc cvaluation of the thcrmal pcrformancc of the Powcrstick and to dctcrminc the amount of thermal insulation nccdcd. It was also used to evaluate the platinum-rhodium clad tcmpcraturc, to assurc hat it remains within its limits.

The RHU acroshcll is made from Finc-Weave-Picrccd Fabric (FWPF) which is a composite of polyacrylonitrilc fibers. This acroshcll has high thermal conductivity in all directions and thus, acts as an cxccllcnt heat collector for the thcrmoclcctric convcrtcr. Bccausc of the low thcrmal fluxes and high thermal conductivity of the acroshcll, the outside of the RHU is nearly isothermal even when most of its thcrmal power is dircctcd through a relatively small area of onc cnd of the RH U. The configuration that was chosen for the Powcrstick convcrtcr dcsign, was to locatc a single thcrmoclcctric convcrtcr on the ccntcr line of onc cnd of the RH U and surround the pcrimctcr and other cnd of the RHU with thcrmal insulation.

A thermal analysis was carried out for two different kinds of thermal insulation, MIN-K 1301, which is produced by Johns-Man nvillc, was examined, assuming that it would operate in a vacuum environment. MI N-K 1301 has a maximum scrvicc tcmpcraturc of 700° C and a dcnsity of 0.4 gram/cm^3. Its thermal conductivity in vacuum, at the assumcd operating conditions of 300 K to 500 K, is 1 x 10^{-4} W/cm-K. The sccond thcrmal insulator material that was cvaluatcd was a prototype super insulation dcvclopcd by Lindc. It consists of aluminum foils separated by glass fiber paper, which is most cffcctivc in vacuum. Its equivalent thcrmal conductivity is 3 x 10^{-6} W/cm-K, which is 30 times more cffcctivc than MlN-K, however, it is more susceptible to edge and corner 1osscs and could suffer greater degradation should it not bc in a vacuum environment.

In order to force a reasonable fraction of the heat (about 70°/0) through the thcrmoclcctric module, it is ncccssary to surround the RII U with about 30 mm of cvacuatcd MI N-K thermal insulation. It was cstimatcd that an cquivalcnt thermal performance could bc obtained with about 10 layers Or super insulation (about 3 mm of thickness). in addition to the heat which bypasses the modulc, about 5 to 10% of the heat that goes through the module goes through the Kapton andcpoxy, rather than the bismuth-tclluridc thcrmoclcctric material, Additional thcrmal resistance was assumed for the ccl] contacts to the heat source and the radiator, which dccrcascs the cffcctivc tcmpcraturc differential across the bismuth-tclluridc. Bccausc of the low operating tcmpcraturcs, the performance of the bismuth-tclluridc is not cxpcctcd to degrade significantly with time. Howcvcr, the thermal power of the RHU dccrcascs with time which will dccrcasc the power from the thcrmoclcctric convcrtcr as a result of dccrcascd thermal input and a dccrcascd tcmpcraturc gradient.

Thc thermal and electrical performance was evaluated, both at the beginning of life and after 10 years of operation, for 30 mm of cvacuatcd MlN-K thermal insulation. Thcsc results arc summarized in 7'able 1.

TABLE 1

	30 mm MI N-K (vat) (BOL)	30 mm MlN-K (vat) (E OL--10 years)
RHU Power (W)	1.10	1.02
Power thru module (W)	0.77	0.72
Power thru BiTc (W)	0.71	0.68
T--RHU surface (K)	475	460
T--BiTc hot junction (K)	455	441
T--BiTc cold junction (K)	305	304
T--radiator (K)	300	300
Electric Powcr (mW)	42	37
Voltage @ Max. Power (v)	15	14

Both cases, describcd in “1’able 1, were calculated for a module with the samc geometry. It assumed a total of 484 couples connected in scrics and assembled into a single modulc. Erich lcg of each couple was assumed to bc 0,30 mm x 0.30 mm with a length of 30 mm. Surrounding each lcg was assumcd to bc 0,025 mm of Kapton and 0.025 mm of epoxy. Thus, the total cross-section of the modulc is 123 square millimeters (1 1 mm x 11 mm) with a length of 30 millimeters.

ThcRHU and 30 mm of thermal insulation would all package into a cylinder which is 86 millimeters in diamctcr. Onc cnd of this cylinder could provide 5800 square millimeters of radiator arca, which is more than enough area to reject all of the waste heat at 300 K.

Issues

The first area of concern is whether a total of 484 couplcs (968 legs) of such small dimcnsions could bc practically asscmblcd intoa singlc modulc. Lcgs with this cross-section have already been fabricated and clcctrodcs bonded onto thcm. However, if it was desired to deliver the power at 30 VDC, the number of couplcs would need to bc doubled, with a resulting smaller cross-section. Alternatively, if the voltage was reduced to 2 to 5 VDC, the number of couples could bc cut to onc-third to onc-seventh and the individual lcg cross-section increased. If the power were delivered at 2-5 VDC, it could bc up-converted to 15 or 30 volts using already existing technology. The expected conversion efficiency would bc about 80%.

The second area of concern is whether it is possible to keep the thermal insulation cvacuated at all times, The RHU, because of the relatively low tcmperaturc of the plutonium-dioxidc fuel, is cxpcctcd to retain almost all of the inert decay gases and not rclcasc thcm. Thcrcforc, it should bc possible to seal the RHU, thermal insulation and convcrtcr into a hermetically scaled container. Alternatively, if the Powcrstick were to operate in deep space, it should bc relatively simple to assure a vacuum environment for any thermal insulation. If the Powcrstick were to operate on the surface of Mars, the atmospheric pressure is cxtremcly low and probably would not degrade the thermal insulation cffectivcness significantly.

A third area of concern relates to the safety of bismuth-telluridc. If bismuth h-telluridc is exposed to supcrheated steam, the tellurium could react with hydrogen to form hydrogen-tclluridc which is a toxic gas, Tests have been performed, and it is known that if bismuth h-telluridc is put into room tcmperaturc water, no reaction takes place. It was estimated that it would require interaction with supcrheated steam at 200 to 300°C before any significant reaction would take place. Thcrcforc, it docsn’t seem like an intractable safety issue, especially considering the very small amounts of material involved (-2 grams of BiTc). However, it is an issue that will need further consideration.

The authors plan to address all concerns during the ongoing prototype dcvclopmcnt.

Acknowledgments

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References

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